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13. ABSTRACT (Maximum 200 words)

Our long-term goals are twofold. First, to explore the new properties of gaseous Bose-Einstein condensates and advance our understanding of quantum gases. Second, we want to use Bose condensed gases as new atom sources of unprecedented brightness ("atom lasers") for precision atom optics and precision metrology.

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Technical Section (Including Objective, Approach, and Progress)

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Technology Transfer

Our current effort includes the development of new techniques to manipulate coherent atomic matter. A long-term prospect is that coherent atom sources based on Bose-Einstein condensation may replace conventional atomic beams in demanding applications. This includes atom interferometry, precision measurements, future atomic clocks (which provide the time and frequency standard), matter wave microscopy, and the creation of microscopic structures by direct-write lithography. The techniques which we have developed may improve future sensors for rotation based on matter-wave gyroscopes.

ONR Database Statistics

9	Papers Published in Refereed Journals Citing ONR Support	1	Papers In Press in Refereed Journals Citing ONR Support
2	Books or Chapters Published Citing ONR Support	3	Books or Chapters in Press Citing ONR Support
2	Technical Reports & Non-Refereed Papers	0	Invention Disclosures Citing ONR Support
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50	Presentations	4	Degrees Granted
1 *(total)*; 0 *(women)*; 0 *(minority)*	PICOPI	1 *(total)*; 0 *(women)*; 0 *(minority)*	Grad Students
0 *(total)*; 0 *(women)*; 0 *(minority)*	Post Docs		

Refereed Journal Articles

1. A.P. Chikkatur, A. Görlitz, D.M. Stamper-Kurn, S. Inouye, S. Gupta, and W. Ketterle:
Suppression and enhancement of impurity scattering in a Bose-Einstein condensate.
Phys. Rev. Lett. 85, 483-486 (2000).

2. R. Onofrio, D.S. Durfee, C. Raman, M. Köhl, C.E. Kuklewicz, and W. Ketterle:
Surface excitations of a Bose-Einstein condensate.
Phys. Rev. Lett. 84, 810-813 (2000).

3. S. Inouye, T. Pfau, S. Gupta, A. P. Chikkatur, A. Görlitz, D.E. Pritchard, and W. Ketterle:
Observation of phase-coherent amplification of atomic matter waves.
Nature 402, 641-644 (1999).

4. W. Ketterle:
Bose-Einstein condensation in dilute atomic gases: atomic physics meets condensed
matter physics.
Proceedings of the 22nd International Conference on Low Temperature Physics (LT 22).
Physica B 280, 11-19 (2000).

5. C. Raman, M. Köhl, R. Onofrio, D.S. Durfee, C.E. Kuklewicz, Z. Hadzibabic, and W.
Ketterle:
Evidence for a critical velocity in a Bose-Einstein condensed gas.
Phys. Rev. Lett. 83, 2502-2505 (1999).

6. J. Stenger, S. Inouye, D.M. Stamper-Kurn, A.P. Chikkatur, D.E. Pritchard, and W.
Ketterle:
Bragg spectroscopy and superradiant Rayleigh scattering in a Bose-Einstein condensate.
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7. D.M. Stamper-Kurn, A.P. Chikkatur, A. Görlitz, S. Inouye, S. Gupta, D.E. Pritchard, and
W. Ketterle:
Excitation of phonons in a Bose-Einstein condensate by light scattering.
Phys. Rev. Lett. 83, 2876-2879 (1999).

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Ketterle:
Superradiant Rayleigh scattering from a Bose-Einstein condensate.
Science 285, 571-574 (1999).

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Ketterle:
Quantum tunneling across spin domains in a Bose-Einstein condensate.
Phys. Rev. Lett. 83, 661-665 (1999).

Books and Chapters

1. W. Ketterle, D.S. Durfee, and D.M. Stamper-Kurn:
Making, probing and understanding Bose-Einstein condensates.
In Bose-Einstein condensation in atomic gases, Proceedings of the International School of
Physics "Enrico Fermi", Course CXL, edited by M. Inguscio, S. Stringari and C.E. Wieman
(IOS Press, Amsterdam, 1999) pp. 67-176.

2. W. Ketterle and C. Raman:

Collisions at nanokelvin temperatures in Bose-Einstein condensates.
In: The Physics of Electronic and Atomic Collisions, Proceedings of the XXI International Conference in Sendai, Japan, 1999, editors Y. Itikawa, K. Okuno, H. Tanaka, A, Yagishita, M. Matsuzawa (American Institute of Physics, Melville, New York, 2000) pp. 23-43.

Technical Reports

1. W. Ketterle:
Experimental studies of Bose-Einstein condensation.
Physics Today, December 1999, pp. 30-35.

2. W. Ketterle:
What does a Bose-Einstein condensate look like?
Optics&Photonics News, December 1999, p. 38.

Presentations

1. Manipulating and probing Bose-Einstein condensates with light.
Gordon Conference on Atomic Physics, Plymouth, NH, July 7, 1999.
(Talk by D.M. Stamper-Kurn).

2. New optical tools to study BEC.
Conference on Macroscopic Quantum Coherence Phenomena, Trieste, 7/5-9/1999.
(Talk by C. Raman)

3. Recent Experiments in Bose-Einstein condensation: Superradiance and critical velocities.
1999 Fundamental Problems in Quantum Theory Workshop, 8/8-13/99, Baltimore.
(Talk by R. Onofrio)

4. Collisions at nanokelvin temperatures in Bose-Einstein condensates.
XXI International Conference on The Physics of Electronic and Atomic Collisions (ICPEAC) in Sendai, Japan, 1999, plenary talk 7/24/1999.

5. Les Houches Summer School on Bose-Einstein condensation, four lectures, 7/27 - 8/3/1999.

6. Bose-Einstein condensation in dilute atomic gases - atomic physics meets condensed matter physics.
XXII International Conference on Low Temperature Physics, 8/4/1999, Espoo, Finland, Plenary Talk.

7. Recent Advances in Bose-Einstein Condensation.
EPS-11: Trends in Physics, 9/10/1999, London, Plenary Talk.

8. Keeping the focus on Bose-Einstein condensates.
European research conference on Bose-Einstein condensation, San Feliu, Spain, 9/13/99.

9. Spectroscopy of a Bose-Einstein condensate.
Inspired by Herzberg: Spectroscopy for the Year 2000, Symposium in memory of Gerhard Herzberg, Cornwall, Ontario, Canada, 10/30 - 11/3.

10. When Laser-Like Atoms Meet Laser Light.
2000 AAAS Annual Meeting and Science Innovation Exposition.
2/21/2000, Washington DC.

11. Shedding light on Bose-Einstein condensates.
International Symposium on Quantum Fluids and Solids, QFS 2000, University of
Minnesota, June 6-11, 2000.
(Talk by D.M. Stamper-Kurn)

12. New light on Bose-Einstein condensates.
ICAP 2000, Florence, June 4-9, 2000.

13. New Light on Bose-Einstein Condensates.
DAMOP 2000, Storrs, Connecticut, 6/14-17/2000.

14. Experiments on Bose-Einstein condensation.
Three lectures at the Summer School on Bose-Einstein condensates and atom lasers,
Cargese, Corse (France), July 17-25, 2000.

15. Optical Properties of a Bose-Einstein Condensate and Phase-Coherent Matter Wave
Amplification.
Gordon Research Conference "Molecular Electronic Spectroscopy and Dynamics",
New London, New Hampshire, July 30 - August 4, 2000.

Patents

1. None

Honors/Awards/Prizes

· Ananth Chikkatur, a graduate student, was selected as the winner of the 2000 Deutsch
Award for Excellence in Experimental Physics. This award is given every other year to one
graduate student at MIT.
· Shin Inouye is one of the 2000 finalists of the New Focus Student Award of the Optical
Society of America
· Wolfgang Ketterle was awarded the Dannie-Heineman Prize of the Academy of Sciences,
Göttingen, Germany (1999)
· Wolfgang Ketterle was awarded the Benjamin Franklin Medal in Physics (2000)

Other Sponsored Work

Title: Experiments with Trapped Neutral Atoms (this grant)
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Dates: 2/1/96 to 1/31/02

Title: Study of Bose-Einstein Condensates
Agency: Office of Naval Research (AASERT)
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Title: Studies of Bose-Einstein Condensation
Agency: Office of Naval Research (DURIP)
Amount: $95,000
Dates: 3/31/00 to 3/30/01 (non-renewable)

Title: Basic and Applied Research in Electronics
Agency: Army Research Office - JSEP
Amount: $96,250
Dates: 11/10/97 to 1/31/01 (non-renewable)

Title: Atom Interferometry, Atom Optics and the Atom Laser
Agency: Army Research Office (DURIP)
Amount: $117,000
Dates: 3/1/99 to 2/28/01 (non-renewable, currently in no-cost extension)

Title: Atom Interferometry Using a BEC (MURI)
Agency: Yale University
Amount: $984,125 (with D.E. Pritchard)
Dates: $5/1/00 to 4/30/05

Title: Packard Fellow in Science and Engineering
Agency: David and Lucile Packard Foundation
Amount: 575,000
Dates: 9/24/1996 to 9/23/2001 (non-renewable)

Title: Atomic Quantum Gases
Agency: National Science Foundation
Amount: $769,265
Dates: 5/1/95 to 4/30/01 (currently in no-cost extension)

Title: A Program in Ultra-Low Temperature Atomic Physics
Agency: National Science Foundation
Amount: 1,835,464
Dates: 5/1/00 to 4/30/05

Title: Towards Experiments with Bose-Einstein Condensates
Agency: NASA (Initial Award)
Amount: $260,000
Dates: 2/1/98 to 1/31/03

Title: Towards Experiments with Bose-Einstein Condensates
Agency: NASA (Augmentation Award)
Amount: $100,000
Dates: 2/1/98 to 1/31/03

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Title of Research	Experiments with trapped neutral atoms
Principal Investigator	Wolfgang Ketterle
Organization	MIT

Technical Objectives

This section will describe the objectives of the contract

Our long-term goals are twofold. First, to explore the new properties of gaseous Bose-Einstein condensates and advance our understanding of quantum gases. Second, we want to use Bose condensed gases as new atom sources of unprecedented brightness ("atom lasers") for precision atom optics and precision metrology.

Technical Approach

This section will describe the Technical Approach taken by the contractor.

Ultralow temperatures are reached by applying first laser cooling and then evaporative cooling. The atomic samples are isolated using optical and magnetic traps. Bose-Einstein condensates are manipulated by a combination of magnetic fields, optical laser beams and radio frequency radiation, and observed by absorption or dispersive imaging techniques.

Progress

This section will describe the accomplishments for Fiscal Year 2000 for the contract
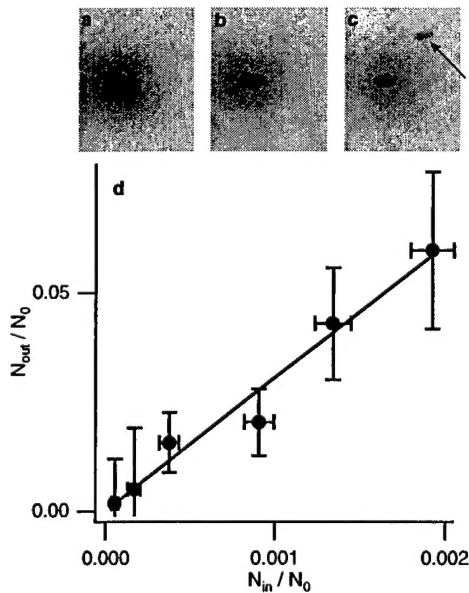
1. Phase-coherent amplification of matter waves

Atom amplification differs from light amplification in one important aspect. Since the total number of atoms is conserved (in contrast to photons), the active medium of a matter wave amplifier has to include a reservoir of atoms. One also needs a coupling mechanism which transfers atoms from the reservoir to an input mode while conserving energy and momentum. We have used the matter wave superradiance which we observed in a BEC [1] to realize a matter wave amplifier [2] (see figure).

Experimental scheme for observing phase coherent matter wave amplification. A small-amplitude matter wave was split off the condensate by applying a pulse of two off-resonant laser beams (Bragg pulse). This input matter wave was amplified by passing it through the condensate pumped by a laser beam. The coherence of the amplified wave was verified by observing its interference with a reference matter wave, which was produced by applying a second (reference) Bragg pulse to the condensate. The interference signal was observed after 35 ms of ballistic expansion. The fringes on the right side show the interference between the amplified input and the reference matter wave. Figure taken from ref. [2].

The gain process can be explained in a semiclassical picture. The input matter wave of wave vector K_j interferes with the condensate at rest and forms a moving matter wave grating which diffracts the pump light with wave vector k_0 into the momentum and energy conserving direction $k_i = (k_0 - K_j)$. The momentum imparted by the photon scattering is absorbed by the matter wave grating by coherently transferring an atom from the condensate into the recoil mode, which is the input mode. The rate of scattering, which is given by the square of the grating amplitude, is proportional to the number of atoms in the input mode N_j, implying an exponential growth of N_j (as long as one can neglect the depletion of the condensate at rest).

Input-output characteristic of the matter-wave amplifier. (a-c) Typical time-of-flight absorption images demonstrating matter wave amplification. The output of the seeded amplifier (c) is clearly visible, whereas no recoiling atoms are discernible in the case without amplification (a) or amplification without the input (b). The size of the images is 2.8 mm x 2.3 mm. (d) Output of the amplifier as a function of the number of atoms at the input. A straight line fit shows a number gain of 30.
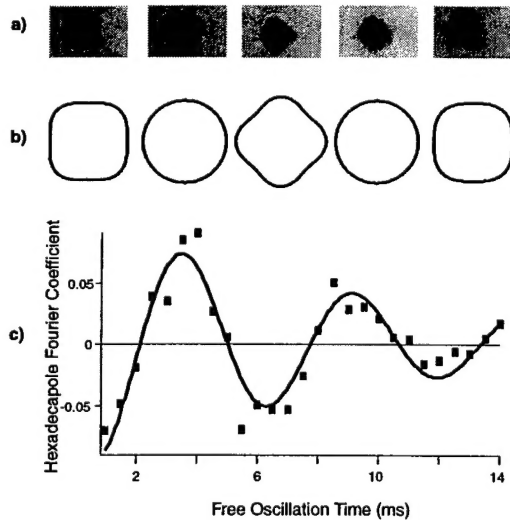
Input matter waves with a well defined momentum were generated by using Bragg scattering to transfer a small part of the condensate into a recoil mode. The input matter wave was amplified by applying an intense radial pump pulse for 20 μs. The number of atoms in the recoil mode was then determined by suddenly switching off the trap and observing the ballistically

expanding atoms after 35 ms of time-of-flight using resonant absorption imaging. After the expansion, the condensate and the recoiling atoms were fully separated (see figure). Phase-coherence of the matter-wave amplifier was demonstrated with an interferometric technique (see figure).

Our experiment can be regarded as a demonstration of an active atom interferometer. It realizes a two-pulse atom interferometer with phase-coherent amplification in one of the arms. Such active interferometers may be advantageous for precise measurements of phase shifts in highly absorptive media, e.g. for measurements of the index of (matter wave) refraction when a condensate passes through a gas of atoms or molecules [3]. Since the most accurate optical gyroscopes are active interferometers [4], atom amplification might also play a role in future matter-wave gyroscopes [5]. In an independent effort a Japanese group [6] has achieved similar results on the amplification of matter waves.

2. Surface excitations in a Bose-Einstein condensate

Collective modes which have no radial nodes and are localized close to the surface of the condensate are called surface modes. In a semiclassical picture these excitations can be considered the mesoscopic counterpart to tidal waves at the macroscopic level. Those excitations are of special interest since they show a crossover between collective and single-particle behavior, which is crucial for the existence of a critical rotational velocity. Furthermore, they probe the surface region of the condensate where the density of the thermal cloud is peaked, and should be sensitive to the interactions between condensed and non-condensed atoms [7].
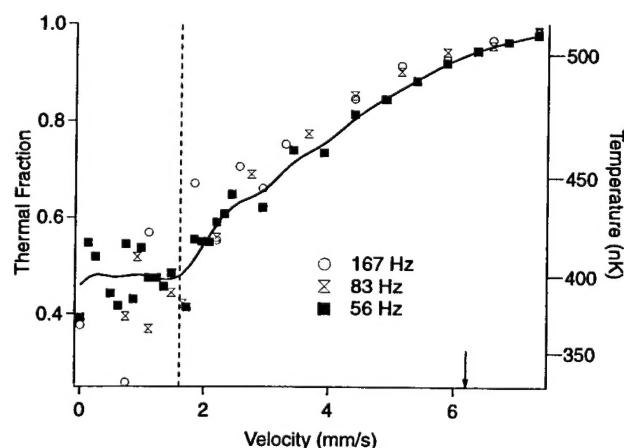

Observation of a standing hexadecapolar excitation of a Bose-Einstein condensate. Absorption images of a condensate driven to excite the $m=4$ mode for various hold times (1, 2, 3.5, 4.5 and 6.5 ms from left to right) in the magnetic trap (a). The shape oscillations of a pure $m=4$ mode are schematically depicted in (b) for one cycle. The contours of images like those in Fig. a were Fourier analyzed. Fig. c shows the oscillation of the $m=4$ Fourier coefficient

Since these modes don't have cylindrical symmetry, they cannot be excited by modulating currents in the coils of a dc magnetic trap. We have therefore developed a method to create perturbations with high spatial and temporal control [8]. Excitations were driven by the optical dipole force of a far-off-resonant focused laser beam which was controlled by a two-axis acousto-optical deflector. A rapid scan created a pattern of two or four points which had the correct symmetry to excite quadrupolar or hexadecapolar surface oscillations. A temporal modulation of the intensity or a rotation of the whole pattern resulted in standing and rotating waves, respectively (see figure).

This novel method should be useful for exciting even higher-lying excitations. It was subsequently used to impart angular momentum to the whole condensate which resulted in vortex formation [9].

3. Evidence for a critical velocity in a Bose-Einstein condensate

The existence of a macroscopic order parameter implies superfluidity of gaseous condensates. Observing frictionless flow is a challenge given the small size of the system and its metastability. We have taken a step towards this goal by studying dissipation when an object was moved through the condensate [10]. This is in direct analogy with the well-known argument by Landau [11] and the vibrating wire experiments in superfluid helium [12]. Instead of dragging a massive macroscopic object through the condensate we used a blue detuned laser beam which repelled atoms from its focus to create a moving boundary condition.

Evidence for a critical velocity. Shown is the final temperature after a laser beam was scanned through the condensate at variable velocity for 900 ms using different scan frequencies. The dashed line separates the regimes of low and high dissipation. The peak sound velocity is marked by an arrow. The data series for 83 and 167 Hz showed large shot-to-shot fluctuations at velocities below 2 mm/sec. The solid line is a smoothing spline fit to the 56 Hz data set to guide the eye.
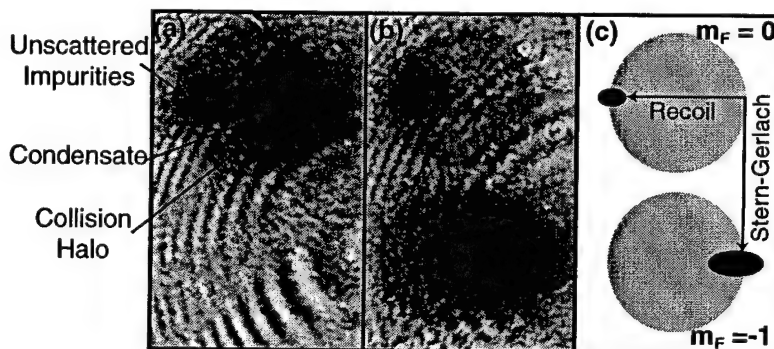
The beam created a "hole" with a diameter of 13 μm which was scanned back and forth along the long axis of the cigar-shaped condensate (Thomas-Fermi diameters of 45 and 150 μm in the radial and axial directions, respectively). After exposing the condensate to the scanning laser beam for about one second, the final temperature was determined. As a function of the velocity of the scanning beam, we could distinguish two regimes of heating separated by a critical velocity. For low velocities, no or little dissipation was observed, and the condensate appeared immune to the presence of the scanning laser beam. For higher velocities, the heating increased, until at a velocity of about 6 mm/s the condensate was almost completely depleted after the stirring. The cross-over between these two regimes was quite pronounced and occurred at a velocity of about 1.6 mm/s which was a factor of roughly four smaller than the speed of sound at the peak density of the condensate (see figure).

These observations are in qualitative agreement with numerical calculations based on the non-linear Schrödinger equation which predict that heating at subsonic velocities is due to the onset of vortex nucleation [13-15]. Because of surface effects and the non-zero temperature, we expect additional corrections leading to dissipation at even lower velocities and a smooth crossover between low and high dissipation. More precise measurements of the heating should allow us to study these finite-size and finite-temperature effects.

4

4. Superfluid suppression of impurity scattering in a Bose-Einstein condensate

The concept of superfluidity applies to both macroscopic and microscopic objects. In both cases, there is no dissipation or drag force as long as the objects move with a velocity less than the so-called critical velocity. A moving macroscopic object creates a complicated flow field. Above a certain velocity, vortices are created. In contrast, the physics of moving impurities, which are microscopic objects, is much simpler. At velocities larger than the Landau critical velocity, they will create elementary excitations, phonons or rotons in the case of liquid helium-4.
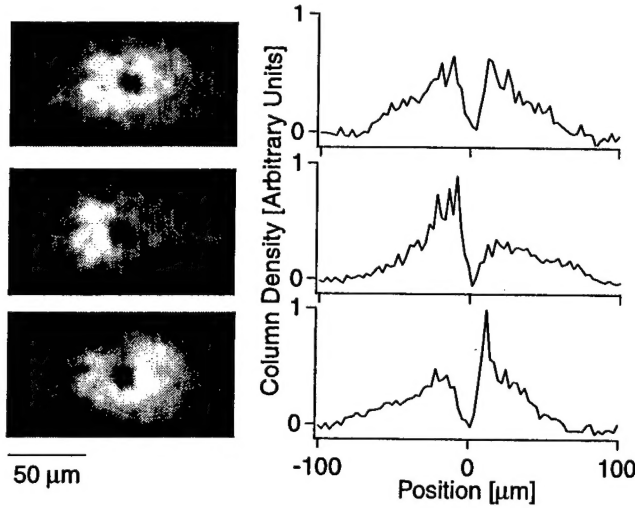
We could create impurity atoms in a trapped BEC by transferring some of the atoms into another hyperfine state using an optical Raman transition. The photon recoil and therefore the velocity of the impurity atoms was varied by the angle between the two laser beams. Collisions between the impurity atoms and the condensate were observed as a redistribution of momentum when the velocity distribution was analyzed with a ballistic expansion technique. The collisional cross section was dramatically reduced when the velocity of the impurities was reduced below the speed of sound of the condensate, in agreement with the Landau criterion for superfluidity [16].

Observation of collisions between the condensate and impurities. The impurities in the m=0 hyperfine state traveled at 6 cm/s to the left. Collisions redistribute the momentum over a sphere in momentum space, resulting in the observed halo (a). In figure (b), the impurities and the condensate in the m=-1 state were separated with a magnetic field gradient during the ballistic expansion. The effect of collisions is to slow down some of the impurity atoms and speed up the condensate atoms. The absorption images are 4.5 mm times 7.2 mm in size.

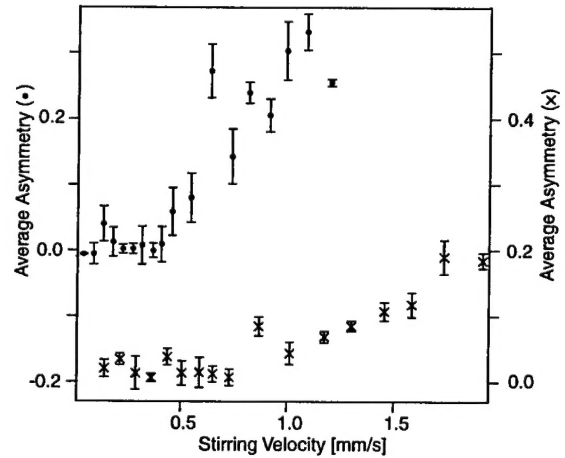## 5. Dissipationless flow and superfluidity in gaseous Bose-Einstein condensates

In our previous work (see above, and [10]), we found evidence for a critical velocity in a condensate. The Bose-Einstein condensate was stirred with a laser beam at variable velocity, and the onset of dissipation was observed by monitoring the temperature of the sample. We have studied the same system by observing the condensate during the stirring using repeated *in situ* non-destructive imaging of the condensate. These images show the distortion of the density distribution around the moving object, thus directly probing the dynamics of the flow field [17].

Pressure difference across a laser beam moving through a condensate. On the left side *in situ* phase contrast images of the condensate are shown, strobed at each stirring half period: beam at rest (top); beam moving to the left (middle) and to the right (bottom). The profiles on the right are horizontal cuts through the center of the images. The stirring velocity and the maximum sound velocity were 3.0 mm/s and 6.5 mm/s, respectively.
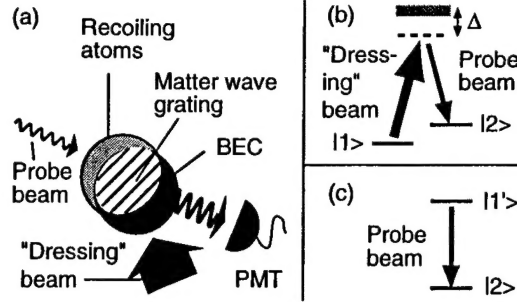
The distortion or asymmetry of the flow is proportional to the drag force and a sensitive indicator for dissipation. The onset of dissipation was found at a critical velocity of about 10 % of the speed of sound which corrects the higher value found previously with a less sensitive method [10]. A comparison of the new technique observing the drag force to the calorimetric method showed good agreement.

Density dependence of the critical velocity. The onset of the drag force is shown for two different condensate densities, corresponding to maximum sound velocities of 4.8 mm/s (solid circles, left axis) and 7.0 mm/s (crosses, right axis). The stirring amplitudes are 29 μm and 58 μm, respectively. The two vertical axes are offset for clarity. The bars represent statistical errors.

6. Amplification of light and atoms in a Bose-Einstein condensate

Bose-Einstein condensates illuminated by an off-resonant laser beam ("dressed condensates") were used to realize phase-coherent amplification of matter waves (see above, and [2, 6]). The amplification process involved the scattering of a condensate atom and a laser photon into an atom in a recoil mode and a scattered photon. This four-wave mixing process between two electromagnetic fields and two Schrödinger fields became a self-amplifying process above a threshold laser intensity, leading to matter wave gain. However, the symmetry between light and atoms indicates that a dressed condensate should not only amplify injected atoms, but also injected light.
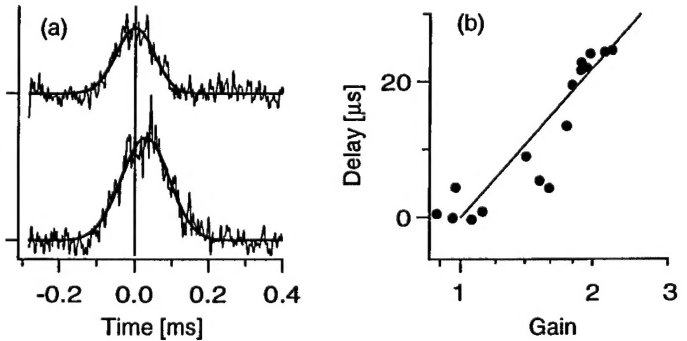
6

Amplification of light and atoms by off-resonant light scattering. (a) The fundamental process is the absorption of a photon from the "dressing" beam by an atom in the condensate (state |1⟩), which is transferred to a recoil state (state |2⟩) by emitting a photon into the probe field. The intensity in the probe light field was monitored by a photomultiplier. (b) The two-photon Raman-type transition between two motional states (|1⟩, |2⟩) gives rise to a narrow resonance. (c) The dressed condensate is the upper state (|1'⟩) of a two-level system, and decays to the lower state (recoil state of atoms, |2⟩) by emitting a photon. Since the system is fully inverted, there is gain for the probe beam.

We have studied the optical properties of a dressed condensate above and below the threshold for the matter wave amplification [18]. The optical gain below the threshold has a narrow bandwidth due to the long coherence time of a condensate. The gain represents the imaginary part of the complex index of refraction. A sharp peak in the gain implies a steep dispersive shape for the real part of the index of refraction $n(\omega)$. This resulted in an extremely slow group velocity for the amplified light. The figure shows that light pulses were delayed by about 20 μs across the 20 μm wide condensate corresponding to a group velocity of 1 m/s. This is one order of magnitude slower than any value reported previously [19].

Above the threshold to matter wave amplification, we observed non-linear optical behavior. Thus we could map out the transition from single-atom gain to collective gain.

Pulse delay due to light amplification. (a) Amplification and 20 μs delay were observed when a Gaussian probe pulse of about 140 μs width and 0.11 mW/cm² peak intensity was sent through the dressed condensate (bottom trace). The top trace is a reference taken without the dressed condensate. Solid curves are Gaussian fits to guide the eyes.
(b) The observed delay time was proportional to ln(g), where g is the observed gain.

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1. S. Inouye, A.P. Chikkatur, D.M. Stamper-Kurn, J. Stenger, D.E. Pritchard, and W. Ketterle, Science **285**, 571 (1999).
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